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Research Article

An Assessment of Social and Ecological Factors Influencing the Management and Productivity of Smallholder Aquacultural Systems in Northern Province, Zambia

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Smallholder fish farmers in Zambia face complex social and ecological challenges. Previous studies have highlighted limitations to productivity in Northern Province, where rates of poverty are high and farmers lack access to essential inputs and markets. Stakeholders emphasize research is needed to understand aquaculture's functions at household and farm scales. Innovations to improve productivity must consider agroecological contexts, local knowledge, and adaptations to situate aquaculture within local livelihood. A study was conducted in Luwingu District to assess productivity and understand farmer perceptions. Data collection (Oct–Dec 2021) engaged fish farmers ($n = 63$) in surveys, farm appraisals, and discussions. Qualitative data highlighted farmers' perspectives, and thematic review identified their major challenges. Quantitative data described household demographics, priorities, resources, and management systems. Multivariate techniques (principal components analysis [PCA]) assessed variation within the sample, reduced data complexity, and created sets of composite variables describing system inputs. Multiple linear regression tested effects of inputs on pond productivity (kg Fish m^{-2}); and stepwise elimination identified key factors. Results indicated that farmers considered aquaculture a secondary economic activity, contributing an average of only $9\% \pm 12\%$ to household income. Most farmers used household labor, basic tools, and crop waste as inputs. The mean output (1.2 ± 1.2 t fish ha^{-1}) was low. Predictive models indicated household wealth, education, farm size, intensity of feed, fingerling and labor inputs, fish growth cycles, and spatial integration with cropland were most associated with aquacultural productivity. Farmers emphasized that limited finances, high costs, and inconsistent local supplies of quality inputs were major challenges. Potential pathways for change are discussed, and recommendations for additional research are offered.

Keywords: farmer perception; mixed methods; smallholder; system management; tilapia; Zambia

1. Introduction

Aquaculture is a key strategy for improving food and nutritional security at both national and household levels in the country of Zambia [1]. At the household level, fish are rich sources of protein, fatty acids, micronutrients, and vitamins, and increased accessibility can reduce rates of malnutrition [2]. Recent research in Zambia has demonstrated that increased consumption of fish among pregnant/lactating women and children is a feasible strategy to improve diets and address mother and infant nutrient deficiencies [3]. As an income-generating activity (IGA), aquaculture has been linked to increases in household purchasing power and access to more diverse diets [4]. Furthermore, aquaculture is promoted by development experts as an agroecological innovation in African smallholder contexts [5]. Integrated arrangements of aquaculture, crop, and livestock systems can generate mutually beneficial interactions among small farm enterprises, resulting in increased "whole farm" productivity [6–8]. Studies from Eastern and Southern Africa have demonstrated aquaculture's contribution to small garden intensification [9], livelihood diversification [4, 9], and efficiencies in water and nutrient regulation [10].

Historically, aquaculture was promoted in Zambia as a means for improving food security within high poverty and rural areas [11]. The result was 'broad adoption of extensive, small-scale farming systems under limited capital and low-quality input regimes, which produce mostly for home consumption or to pay for immediate expenses [12]. More recently, commercial and medium-income aquaculture has experienced rapid expansion, overtaking the smallholder sector in total output [11]. The most successful enterprises have developed near urban and peri-urban areas of southern provinces, where input supply chains of commercial feed, fertilizers, and fingerlings are more accessible and output markets more dependable [12]. As a result, national production has increased from 4240 in 2000–45,670 tons in 2020; making Zambia the 6th largest producer of farmed fish in Africa [13].

Nevertheless, critical challenges have been reported. The aquacultural value chain in its current form is not socially sustainable, nor is the economic growth inclusive, as it overwhelmingly benefits large-scale producers [14]. Recent livelihood assessments highlight the growing production divide between hundreds of farmers in southern regions of the country and thousands of smallholders existing in northern and rural regions [15]. Most of the estimated 9615 smallholders adopting aquaculture in Zambia exist in northern regions, such as Northern and Luapula Provinces. These regions have rich land and water availability, as well as a growing local demand for fish [11]. Unfortunately, farmers in these regions have limited access to commercial supply chains. Previous studies have highlighted high poverty levels, low household purchasing power, lack of extension services, and underdevelopment of roads and market infrastructure as barriers to productivity [15, 16]. For example, commercial feed distributors perceive regions like Northern Province financially risky due to poor road networks and inconsistent demand from smallholders [17]. As a result, most farmers accessing commercial inputs incur high transportation costs since they are located great distances from distribution networks [17]. Supply of quality fingerlings is likewise constrained. Government-run hatcheries, which have historically supplied fingerlings in the region, are underfunded, have reduced capacity, and are unable to fulfill the growing demand from smallholders [11, 14]. Consistent access to technical knowledge and extension services is also a barrier to productivity. Northern regions have low adoption of better management practices in aquaculture, such as appropriate water system management, planning of growing and breeding cycles, feeding strategy, and record keeping [18].

Development stakeholders have emphasized the need for more coordinated strategies to overcome these barriers and support sustainable transitions of smallholders into more productive and business-oriented forms of aquaculture [14]. National efforts focus on essential 'top down' approaches; mainly, expansion of market linkages between the private sector and smallholders to increase access to quality inputs, as well as regional and national output markets [11]. However, experts also agree that transition pathways will require "bottom up" strategies to make aquaculture more affordable, more adapted to different local conditions, and more accessible to poor and marginalized producers [8, 12, 19, 20]. Previous research has been conducted in Zambia to contextualize the social and ecological constraints and opportunities existing for smallholder producers at national and provincial scales. For example, [14] conducted an in-depth value chain study on aquaculture's contribution to national economic growth, inclusiveness, and sustainability. Further, comparisons between early livelihood studies conducted in Northern Province [16], and more recent assessments [15] have highlighted the stagnant nature of management and productivity in the region. Better management practices have been developed for semi-intensive systems [18], however, adoption of these practices remains low. Efforts to promote better management have included a participatory experimental trial that assessed productivity on smallholder farms. An 8-month study conducted by Lundeba et al. [21] identified the effects of local feeding strategies on productivity. Fifteen farmers managed ponds stocked with *O. macrochir* and tested the effects of feeding and fertilization on fish growth and water quality parameters. Results indicated strategies that incorporate homemade feeds comprised of maize and soybean, plus fertilization with livestock manure, can generate modest outcomes for households (19 kg Fish; 0.2 ± 00 kg Fish m^2; [21]).

Despite these initiatives to address management and productivity, stakeholders emphasize that significant gaps in knowledge exist at household and landscape scales. At these scales, aquaculture performs a diversity of functions (i.e., food, income, irrigation, etc.), and so the practice may support productivity through multiple pathways. Viable "bottom up" innovations require the consideration of local knowledge and adaptations to appropriately situate aquaculture within the livelihoods of smallholders [22]. Ecological conditions and social interactions play a central role. Greater understanding of the local-specific social and ecological drivers of farming systems is required to assess production and consumption dynamics, system trade-offs, and transition pathways that can be sustainable for poor or vulnerable farmers [22]. Thus, a case study was conducted in the Luwingu District of Northern Province in 2021 to understand the key social and ecological factors that influence aquacultural productivity (kg Fish m^2) in ($n = 63$) smallholder systems. Specifically, we attempted to: (1) Provide a comprehensive description of smallholder households and aquacultural systems, including variation in management practices existing within the sample. (2) Understand the key social and ecological factors that influence aquacultural productivity (kg Fish m^2) in smallholder systems. (3) Explore farmer perceptions regarding the major challenges experienced when managing aquacultural systems.

2. Materials and Method

2.1. Research Approach. A mixed-method design was used in this study. The mixed methods approach recognizes that diverse sources of data provide a more complete understanding of complex issues or problems under study [23]. Descriptions of households and social-ecological resources were structured within a sustainable livelihood framework (SLF; [24, 25]. Aquacultural development stakeholders in both Africa and Asia have promoted SLF as a tool to inform interventions and policies that support positive outcomes for fish farmers [15, 26, 27]. The SLF was used to guide data collection and analysis in this study. Indicators were selected to describe key components of the framework, including household economic priority, conditions of vulnerability, capital endowment, livelihood strategy, and outcomes.

2.2. Site Characterization

2.2.1. Luwingu District. This study was conducted in Luwingu district. The region has the largest proportion of fish farmers ($n = 421$ farmers, 18%) among all districts in Northern and Luapula provinces [28]. The combined area of Luwingu is 8892 km^2, with a population density of 13.7 inhabitants km^{-2} and an annual population growth rate of 4.2% [29]. The economy is predominately agricultural, with 86% of households engaged in farming as the main economic activity, growing some combination of maize (*Zea mays*), cassava (*Manihot esculenta*), beans (*Phaseolus vulgaris*), and groundnuts (*Arachis hypogaea*) [16]. Agriculture is challenged by limited infrastructure, leached, acidic soils, as well as high rates of soil degradation. The region has high per capita poverty levels (approaching 80%), as well as child malnutrition, stunting, and wasting rates above the national average [30].

The natural landscape is situated on a plateau (1208 m elevation) and consists of patchworks of farms, small towns, miombo woodland, savannah, and extensive networks of wetlands and streams [16]. The abundance of perennial water bodies and favorable climate (Köppen classification *Cwa*) makes Luwingu ideal for both agricultural and aquacultural development. The district lies within Zambia's agro-ecological region III and receives rainfall of over 1000 mm yr^{-1} [16].

2.2.2. Aquaculture in Luwingu District. Households adopting aquaculture commonly manage fewer than five earthen ponds; averaging about 200 m^2 in size, and stocked with native tilapias [18]. Common species in cultivation include Green-Headed Tilapia (*Oreochromis macrochir*) and Red-Breasted Tilapia (*Coptodon rendalli*) [11]. Although these species may be stocked in monoculture or polyculture, the interconnectivity of ponds to surrounding wetland and stream environments results in the entry of wild self-recruiting species. This includes other species within the genus *Oreochromis*, catfish (*Clarias* sp.), mouth-brooders (*Pseudocrenilabrus* sp.), and barbs or minnows (*Enteromius* sp.) [31].

Previous studies have indicated that management exists in various "extensive" and "semi-intensive" forms [14, 15]. Most farmers depend exclusively on family labor, basic agricultural tools, and local sources to supply essential inputs. Fingerlings are acquired from farmer networks or the government-run hatchery in Kasama, then bred for repetitive cycles over multiple years, leading to inbreeding [15]. Common fertilizers and feeds are livestock manures, household wastes, crop byproducts, and in some instances, the formulation of compound feeds using higher quality ingredients [21]. Less than 20% of farmers in the region purchase commercial feeds and fertilizers [28].

As partial pond harvesting and intermittent harvesting for household consumption are common practices, the productivity of systems is difficult to estimate [15]. Most estimates from Northern Province are derived from recall data of systems with varying forms of management, having yields ranging from 0.5 to 3.1 t ha^{-1} [12, 16, 32]. Profit margins of smallholder systems are estimated to be very low, offering mostly *supplementary* income and fish for household consumption [14].

2.3. Survey Methods

2.3.1. Data Collection Instrument. Questionnaires were intended to facilitate participant recall of aquacultural and agricultural activities within the previous year. Sections of the data collection instrument were adapted from several sources. Households and agricultural systems were described using modules from the *RHoMIS* survey [33], including modules related to demographics, food security, land use, crops, livestock, and agroforestry. Sections describing aquacultural systems, including resource access, inputs, outputs, and systems of management, were selected from the WorldFish [34] survey instrument used in the 2018–2019 census of smallholder farmers in Northern and Luapula Provinces [35]. Other queries and pre-codes related to management and challenges to management were derived from GIZ [36]. Experts and stakeholders were consulted to confirm content and face validity of the instrument. Pilot testing ensured participant understanding of inquiries in the survey and queries for open-ended discussion. Pre-tests of research processes and in-depth member-checks were conducted with the first 12 participants in the study. A copy of the survey instrument is available in Johnson [37].

2.3.2. Participant Recruitment. During October of 2021, the Department of Fisheries (DoF) provided a database of 418 known fish-farmers (Luwingu $n = 216$, Lupososhi $n = 202$). The DoF also provided contact information of 4 lead farmers known to culture and sell fingerlings ("fingerling producers"). Using this information, simple random and snowball sampling approaches were conducted concurrently. Individuals were randomly selected from the DoF database. Consenting individuals served as informants regarding other active fish farmers in the area, while fingerling producers served as informants for locating households with stocked ponds. This strategy generated a running list of contacts, from which potential participants were selected. Recruitment sought variation within the target sample ($n = 60$), stratified according to the participant's distance from Luwingu Town (≤20 km vs. >20 km distance from town) and experience in aquaculture (≤5 vs. >5 years). Experienced farmers were prioritized, since available research indicated most fish farmers in the area were recent adopters [28]. Aquaculture is a knowledge-intensive practice, requiring training and personal experience to achieve positive outcomes [9]. Potential participants were contacted by phone or household visitation. Interested individuals were screened to ensure the following inclusion criteria: (a) active fish farmer; (b) having at least 1 year of experience; (c) actively managed at least one pond in the previous year; and (d) verbally consented to visitation. Following screening procedures, interested individuals completed consent forms. This strategy yielded $n = 63$ fish farmers who met inclusion criteria.

2.3.3. Data Collection. Data collection occurred from October through December 2021. Researchers gathered data using a questionnaire containing discrete and open-ended interview questions regarding the household's activities over the previous year. The process adopted for each household assessment included completion of participant consent forms, the interview, and a participant-led farm appraisal. Total mean interview time was ~ 100 min; participants chose the interview setting. Household members wishing to listen to or contribute to conversations were allowed with the participant's permission. Following interviews, farmers led a tour of their farms. Researchers devoted time to rapid rural appraisal [38] and conducting follow-up, open-ended discussions. Tours included homesteads, home gardens, livestock, primary cropping fields, fishponds, and locations of water resource access. Farm tours ranged from 30 to 60 min, depending on farm size and the participant's time and interest.

Surveys described participant and household demographics, capital endowment, economic priorities, and aquacultural system characteristics. During surveys, participants recalled quantities of aquacultural inputs and outputs. Quantities of the following aquacultural input types were estimated: fingerlings, commercial feed, maize bran, homemade *supplementary* feed, livestock manure, urea fertilizer, and D-compound fertilizer. Farmers also recalled system outputs, including fish bulk harvested at the conclusion of growing cycles, as well as fish intermittently harvested throughout the growing cycle. If a participant was unable to recall annual quantities in bulk, data was reported in "times per unit" (i.e. "times per month" or "times per year"). Common household containers with known volumes were used as demonstrations to facilitate reliability of data. The process allowed participants the option to report inputs and outputs in more familiar units like numbers of basins, buckets, bowls, or plates, rather than kilograms.

Ranking exercises explored participant economic priorities. All IGAs performed by the household were listed, then participants selected three IGAs from the completed portfolio and ranked selections according to their importance to the household. Qualitative data included descriptions of farmer perceptions regarding aquaculture management and their self-perceived management challenges. Relevant observations made during farm appraisals were also considered as a data source. Observational data were intended to contextualize management within the larger sample and corroborate findings gleaned from interviews.

To facilitate triangulation, data were collected from multiple sources. Data were captured with audio recordings, field notes, digital camera, and a GPS tracker (Garmin 64S) which recorded locational data every 10 s in an automated track-file. The participant served as the primary source of member checking throughout data collection. Any discrepancies in interview data and direct observation were addressed by researchers and clarified by participants during farm appraisal. The research team engaged in formal debriefing immediately after each participant's encounter. Debriefing included review and discussion of surveys, field notes, and observations.

2.4. Quantitative Analysis. Data describing demographics, resource access, and aquaculture systems were summarized using descriptive statistics. Although differences in sampling techniques precluded statistical comparison to the 2018–2019 census of smallholder farmers in Luwingu District ($n = 373$ farmers; [35]), examination of results from each study revealed marked similarity (see Table S1). To provide visual representation of household locations, a map of homesteads and major landscape features was created using ArcGIS Pro Software [39]. Household and farm system GPS data points were uploaded with feature data from the World Wildlife Fund's terrestrial ecoregions of the world [40] and the Humanitarian Data Exchange's OpenStreetMap [41].

The Spatial Analyst toolbox in ArcGIS Pro was used to generate spatial variables for analysis. For instance, literature suggested farmer access to road and market infrastructures is a key determinant of productivity. In this study, the "near" function in ArcGIS Pro was used to measure distance (km) from each household to Luwingu Town center or a primary road. Additionally, literature has suggested smallholders may intensify aquacultural systems through farm-level efficiencies of space and resource management (i.e. integrated agriculture). Spatial integration of aquacultural and agricultural activities was considered in this study. Within each farm boundary, distances between the GPS points of fishponds and the GPS points of all other farm features (i.e. homesteads, gardens, fields, livestock) were measured. Fishponds were considered "spatially integrated" if existing within 100 m of the homestead, livestock housing structures, or croplands.

Raw data describing quantities of system inputs and outputs were converted to standard measures for analysis. Volumes reported by farmers were converted to mass using conversion factors of proxy ingredients. The proxy for all homemade feed was maize meal (attribute: 0.64 kg L^{-1}; [42]). The proxy for all cereal brans was maize bran (attribute: 0.31 kg L^{-1}; [42]). A singular estimate for total feed (kg feed m^{-2} yr^{-1}) was calculated by aggregating reported quantities of commercial feed, supplementary feed, and bran. Livestock manure reported in kilograms of dry matter was converted into grams of elemental nitrogen using the attributes of goat manure as proxy for all manure types (attribute: 17 g N kg^{-1}; [43]). Reported urea and D-compound fertilizer quantities were also converted into elemental nitrogen [44]. Following these conversions, manure, urea, and

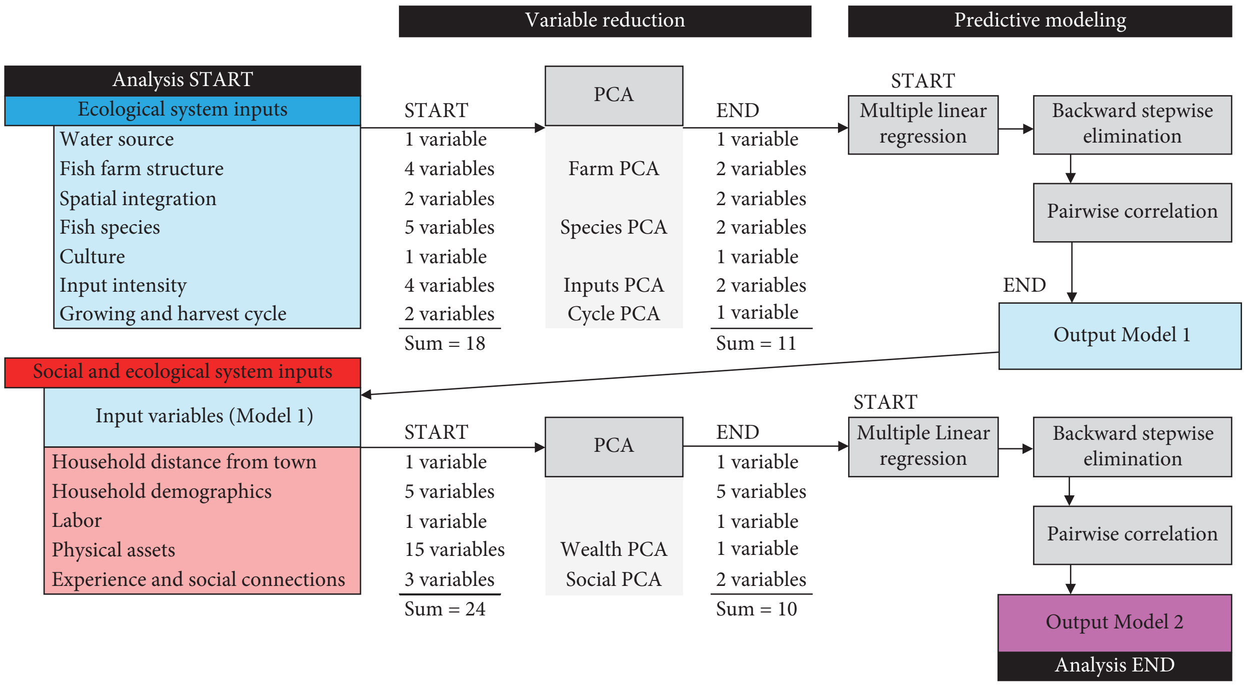


Figure 1: Analysis flow diagram showing datasets selected for variable reduction using PCA, as well as social and ecological input variables used to predict productivity (kg Fish m²).

D-compound inputs were aggregated into a singular rate of elemental nitrogen (g N m^{-2} yr^{-1}) for analysis. Regarding fish outputs, farmer-reported volumes of harvested fish were converted to mass using a standard ratio developed by researchers [37]. A volume-to-mass conversion ratio was established and used for all output data (0.712 kg fish L^{-1}). All estimates of input and output quantities were divided by the area of the active pond prior to statistical analysis.

Analysis of the social and ecological factors that influenced productivity was performed in stages (depicted in Figure 1). Statistics were implemented using analysis, extraction, and visualization packages in R statistical software [45]. Distributions of continuous data were initially inspected using QQ plots to ensure conditions of normality were met, and logarithmic transformations were performed as needed. Multivariate techniques were used to reduce data complexity, as many variables were inter-related. Data was disaggregated into subsets, with selected variables grouped according to descriptions of physical wealth, social organization, farm structure, fish species, input intensity (i.e. fingerlings, feed, fertilizers), as well as fish growing and harvesting cycles. Within each subset, a principal components analysis (PCA) condensed correlated variables to uncorrelated composite variables [46]. Composite variables, known as principal components (PCs), retain much of the variation present, as they are a linear combination of the original data. Results of the PCAs were discussed in PC "loadings," which are coefficients equal to the eigenvectors of the correlation or covariance matrices. Absolute PC loadings greater than 0.50 indicate strong association among the variables used to create a particular PC; and thus, loadings are often used to define and name the given PC [46].

Multiple linear regression was used to test the effects of individual and composite variables on pond productivity (kg Fish m^{-2}; see Figure 1). Two regression models were conducted. Model 1 tested variables describing ecological system functions only. Backward stepwise elimination was performed using comparisons of the Akaike information criterion (AIC) to identify the variable combination providing best balance between model fit and variable complexity compared to the starting model. Ecological variable combinations identified in Model 1 were subsequently used as inputs in Model 2, which also considered effects of social variables. Stepwise elimination procedures were repeated for Model 2. A pairwise correlation matrix was constructed to understand interactions between explanatory variables.

2.5. Qualitative Analysis. During interviews and open-ended discussions, participants were asked to describe up to three major challenges they faced when managing aquacultural systems. Questionnaires contained a qualitative codebook of a priori selected themes. Pre-coded options were used to note major emergent themes; however, codes were not shared or discussed with participants. The process resulted in 186 responses, pre-coded by the major theme. Subthemes within the domain of each major theme were determined through a comprehensive review of all data generated from audio recordings, transcripts, photographs, notes, and observations. Methods outlined by Creswell and Creswell [23] assured consistency of approach and supported accuracy of findings (pp. 190–198). Data were reviewed using an iterative process, working progressively and systematically through all text and images. When coding of sub-themes was complete, data were summarized within the domain of major themes.

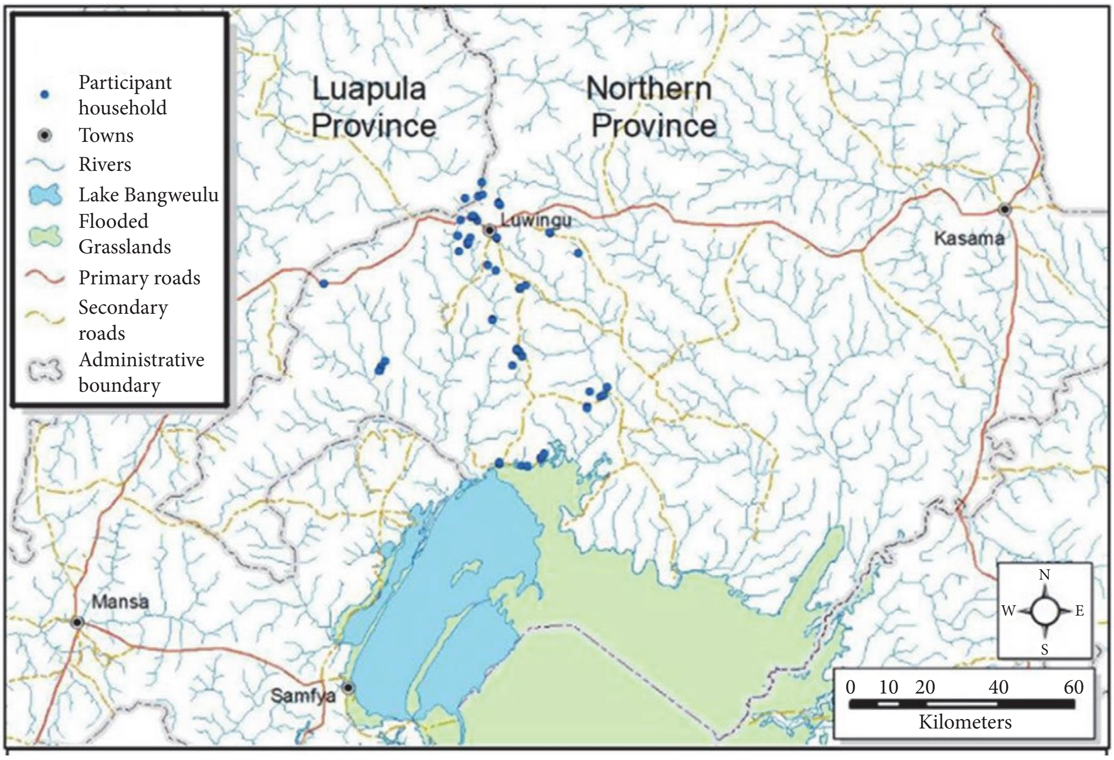


FIGURE 2: Location of $n = 63$ participant households.

To facilitate credibility of qualitative findings, the investigator adopted standards of rigor ([23]; pp. 200–202). Firstly, the researcher's personal bias was addressed prior to the study by considering personal beliefs, prior experiences, and assumptions. The following criteria were also addressed: triangulation, member checking, peer debriefing, long-term observation, and informal peer-debriefing with development stakeholders. An auditable decision trail was maintained. Audio recordings were transcribed into English by an accredited local-language expert. Transcripts were thoroughly reviewed by the investigator to identify discrepancies, typographical errors, or seek clarification or context from the translator when dialect or phrase meanings complicated direct translations. Thematic analysis was cross-checked in several stages by both the investigator and peer reviewers. Coding was iteratively examined to ensure that data fit emerging themes.

3. Quantitative Results

3.1. Descriptive Summary. A map of the study area indicating major geographic features and location of sampled households is provided in Figure 2. Tables 1 and 2 present statistical summaries of survey data related to demographics and aquacultural systems. Observational data and relevant photographs are available in Supporting Figures S1–S8. A narrative summary of key variables describing participant and household demographics, household economic priorities, and aquacultural systems is also provided.

3.1.1. Participant and Household Demographics. Participant ages ranged from 24 to 79 years and averaged 49 ± 12.6 years. Experience in aquaculture ranged from 1 to 36 years. Most fish farmers were married men, having a primary or junior-secondary level of education. A smaller proportion of households (11%) were headed by single or widowed females. The participants' households were comprised of an average of 7.0 ± 2.6 members.

3.1.2. Household Livelihood. Aquaculture was an ancillary economic activity for most households. On average, aquaculture contributed only 9% to household income, while agriculture and nonfarm activities contributed 66% and 25%, respectively (Table 1). Figure 3 illustrates an inventory of household economic priorities, as well as participant rankings of IGAs according to their relative importance to the household. Production of staple crops was frequently ranked as most important. Aquaculture was nearly always ranked as secondary or tertiary to other IGAs. Notably, 49% of fish farmers reported the ownership of a small business, and only 20% reported formal, waged employment.

3.1.3. Household Assets. Total disposable income ranged widely (Table 1) and averaged $16{,}584 \pm 17{,}797$ ZMW ($962 ± 1032; mean exchange Oct–Dec 2021: $1\,K = 0.058$ USD, exchange-rates.org). An inventory of physical assets (Table 2) revealed that most farmers owned only basic agricultural tools; more specialized equipment for aquaculture was infrequent. For example, less than 15% of farmers owned a seine. Labor for aquacultural activities was primarily provided by household members, with 62% hiring additional labor mainly for pond harvesting or construction activities. Less than half of farmers (43%) were members of an aquacultural cooperative; frequently

Table 1: Descriptive statistics; continuous variables describing social and ecological systems.

(a) Social system input	Min	Q1	Median	Mean	Q3	Max	Log trans[a]
Access to road and market infrastucture							
Distance to town or primary road (km)	0.1	5.2	9.9	21.7	32.8	63.4	●●
Household demographics							
Head age (years)	24	40	49	49.1	57	79	
Head education (score)[b]	1	1	2	1.9	3	3	
Household size (persons)	2	5	7	7.0	8.5	12	
Experience and social connections							
Experience in aquaculture (years)	2	3	5	6.8	8	36	●
Visits with extension officer (number)	0	0	2	2.0	3	12	●●
(b) Ecological system input	**Min**	**Q1**	Median	**Mean**	**Q3**	**Max**	**Log Trans[a]**
Fish farm structure							
Active pond area (m^2)	70	250	446	641	747	3450	●
Number of active ponds	1	2	2	2.7	3	7	●
Cultivated land (ha)	0.6	1.5	2.3	2.5	3	10	●
Tropical livestock unit (TLU)[c]	0.00	0.18	0.43	0.74	1.05	3.30	●●●
Growth and harvest							
Growing cycle (Months)	0	3	8	9.2	12	36	●●
Intermittant havest (% Fish yield)	0%	3%	24%	38%	73%	100%	
Input intensity							
Stock rate (fingerlings m^{-2})	0.0	0.3	0.8	1.4	2.0	7.0	●●●
Nitrogen rate (g N m^{-2})	0	2.9	9.1	13.4	19.5	67.5	●●
Feed rate (kg Feed m^{-2})	0	0.1	0.2	0.4	0.5	2.9	●●●
% Commercial feed	0%	0%	0%	16%	45%	100%	
(c) Social ecological system output	**Min**	**Q1**	**Median**	**Mean**	**Q3**	**Max**	**Log Trans[a]**
Farm output							
Productivity (kg Fish m^{-2})	0.00	0.04	0.08	0.12	0.14	0.82	●●●
Fish yield (kg)	2	14	31	68	74	880	
Household consumption							
Fish consumed (% kg)	1%	25%	50%	55%	95%	100%	
Income generation							
Total disposable income (ZMW)[d]	1500	4842	10,000	16,584	21,250	86,000	
Aquaculture (% ZMW)	0%	0%	5%	9%	14%	50%	
Agriculture (% ZMW)	5%	41%	71%	66%	93%	100%	
Off-Farm (% ZMW)	0%	0%	19%	25%	47%	92%	

[a]Variable requiring Log Transformation prior to analysis: '●' = log10 (x); '●●' = log10 $(x+1)$; '●●●' = log10 $(x+0.1)$.
[b]Education Score: 1 = Primary; 2 = Junior Secondary; 3 = Senior Secondary or Tertiary.
[c]TLU conversion factors: cattle = 0.70; sheep and goats = 0.10; pigs = 0.20; poultry = 0.01.
[d]Oct–Dec 2021 mean ZMW exchange rate 1 ZK = \$0.058 USD [exchangerates.org].

reported sources of information were fellow fish farmers (89%) and government extension (57%) (Table S1).

3.1.4. Farm Structure. Sampled households cultivated an average of 2.5 ± 1.7 hectares of land (Table 1) divided among 3 ± 2 fields. Households cultivated 11 ± 3 crop species and 4 ± 2 tree species, on average. The most frequently reported crops were maize (94%), groundnuts (88%) cassava (81%), sweet potato (81%), pumpkin (71%), and beans (70%). Small gardens contained rapeseed leaf (84%), tomato (80%), and Chinese cabbage (71%). Livestock ownership was minimal (Table 1). Households owned an average of 2 ± 1 species of livestock (chickens [84%], goats or sheep [46%], and swine [22%]).

Analysis of homestead, fishpond, livestock housing, and cropland GPS locations identified integrated arrangements of farm features. Distance between the homestead and fishponds varied widely (0.0–8.36 km), however, farmers traveled an average of 0.77 ± 1.46 km to reach their fishpond. Only 15 farms (24%) contained fishponds within 100 m of the homestead. In all cases of livestock ownership, animal housing structures were found within 100 m of the homestead. Thirty-one farmers (49%) managed ponds within 100 m of cropland, including dry season field crops and small gardens.

3.1.5. Aquacultural Systems. All households managed hand-dug, earthen ponds. Nearly all farmers (97%) reported that

TABLE 2: Descriptive statistics; binary variables describing social and ecological systems.

(a) Social system variable	No.	%
Participant demographics		
Head family	7	11
Labor		
Hired labor in aquaculture	39	62
Experience and social connections		
Aquaculture cooperative member	27	43
Physical assets		
Iron-sheeted roof	50	79
Cement floor	38	60
Solar panel/battery	51	81
Electricity (ZESCO transmission)	3	5
Refrigerator	4	6
Mobile phone	62	98
Radio	47	75
Television	31	49
Bicycle	57	90
Motor vehicle	6	10
Wheelbarrow	15	24
Seign net	9	14
Water pump	6	10
Genset and water tank	1	2
(b) Ecological system inputs	**No.**	**%**
Spatial integration		
Pond within 100 m of household	15	24
Pond within 100 m of cropland	31	49
Water source		
Surface water	17	27
Culture		
Monoculture	26	41
Fish species		
Oreochromis sp.	52	83
Coptodon rendalii	47	75
Tilapia sparmanii	13	21
Other fish species	8	13

water was available all year for aquacultural activities. Most farmers (73%) accessed groundwater or natural spring water near pond production areas, while others (27%) sourced water from rivers or streams through networks of farmer-managed or community-managed furrows (Figure S7). Households owned, on average, 5 ± 4 total ponds and 3 ± 2 actively managed ponds. The mean active pond area was about $641 \pm 636\,m^2$, with individual ponds averaging $221 \pm 142\,m^{-2}$ in size.

Ponds were stocked with *C. rendalii* and species within the genus *Oreochromis* (Table 2). Relatively few farmers stocked other species. Over half (54%) of farmers recycled on-farm brooders or fingerlings. Fingerlings were purchased either from fellow fish farmers (33%) or the government hatchery in Kasama (13%). The reported number of fingerlings stocked (548 ± 638 fish per growing cycle) varied widely. Food waste and vegetation were the most frequently reported input (92% of farmers). Only 16 farmers (29%) accessed commercial feed. Homemade mashes and maize bran were more frequently reported (59% and 33% of farmers, respectively) as feed inputs. Farmers added an average of 184 ± 229 kg of feed to their fishpond, achieving a mean feeding rate of 0.39 ± 0.52 kg feed m^{-2}. Most farmers (87%) fertilized their ponds with livestock manure, with 48% reporting smaller additions of chemical fertilizers. Mean additions of manure and chemical fertilizers were 257 ± 330 and 10 ± 39 kg, respectively, resulting in a mean fertilization rate of $13.4 \pm 13.6\,g\,N\,m^{-2}$.

The mean period between stocking and bulk harvest was 9.2 ± 8.2 months. Few farmers (11%) reported completely harvesting their fishponds during bulk harvests. Partial pond harvesting for preservation of fingerlings or brooders was more frequent. Rather than delaying until the final harvest, most farmers (68%) intermittently harvested small numbers of fish during the growing period. Households obtained an average of $38\% \pm 39\%$ of total yields from intermittent harvests.

The average amount of fish harvested was low (Table 1). Only 29 farmers (46%) qualified output as a "good harvest." Only 12 farmers (19%) reported yields of $2.0\,t\,ha^{-1}$ and above. Households utilized an average of 55% of harvested fish for home consumption and 45% for income generation. Farmers sold fish to neighbors, either at farm-gate or nearby village markets. Only in a few cases (17%) did farmers access larger commercial buyers in Luwingu Town, such as hotels and restaurants. The average income generated from aquaculture was 1114 ± 2338 ZMW ($\$65 \pm 136$ USD).

3.2. Variable Reduction. Figure 4 depicts two PCAs considering social data subsets. Composite variables generated were as follows: "Wealth," "More Social Connections," and "More Experience" in aquaculture. The PCA of physical wealth indicated ownership of specialized tools in aquaculture was positively correlated with all other assets. All assets were oriented along Dim1, with the strongest coefficients describing housing quality, transportation, and solar energy access. These results were considered meaningful, and Dim1 of the Wealth PCA was transformed into a percentile indicator of "Wealth." The PCA on experience and social connections demonstrated all variables were correlated along Dim1 with "More Social Connections" explaining the greatest variation between farmers. Farmers having "More Experience" were captured along Dim2.

Figure 5 illustrates results from individual PCAs of ecological data subsets. The PCA on farm structure indicated that fishpond size and number explained the greatest variation (i.e. "Small vs. Large Fish Farm"). Large fish farms were positively correlated with the cultivation of cropland and ownership of livestock, with relative differences in ownership represented by Dim2 (i.e. "More Cropland and Livestock"). In the PCA of fish species, data exhibited roughly the same amount of variance along both axes (Dim1 = 37.9% vs. Dim2 = 31.8%), indicating no single dimension meaningfully captured overall data variability. Stocking of "Oreochromis vs. Coptodon," was captured by Dim2, while stocking of all "Other Fish Species" explained variation along Dim1. The PCA on input quantities denoted that total feed, number of fingerlings, and fertilization rates were strongly correlated and oriented

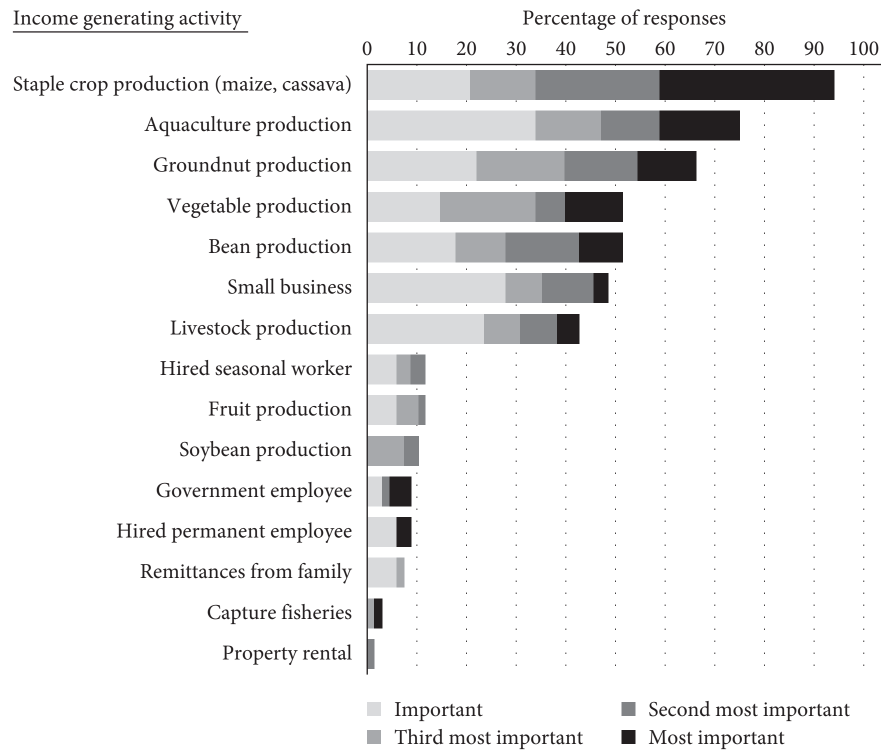
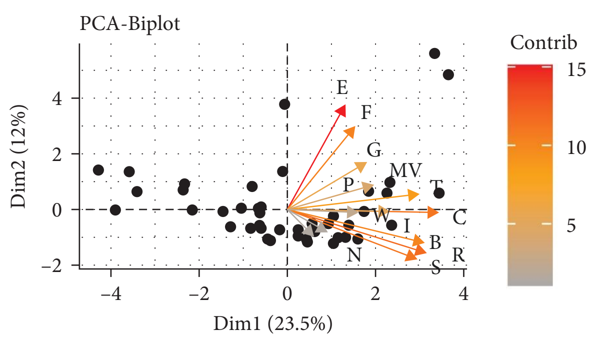


FIGURE 3: Household economic priorities. Participants listed all income-generating activities (IGAs) from the previous year. When the IGA portfolio was complete, the participant selected three IGAs and ranked the selections according to their relative importance.

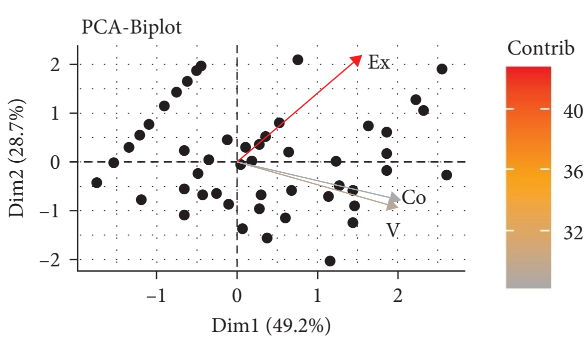


Wealth PCA

KEY		Dim1	Dim2
I	Iron-Sheeted Roof	0.50	−0.02
C	Cement Floor	0.74	−0.03
S	Solar Panel/ Battery	0.64	−0.39
E	Electricity	0.28	0.82
F	Refrigerator	0.33	0.64
P	Mobile Phone	0.21	0.07
R	Radio	0.68	−0.34
T	Television	0.64	0.12
B	Bicycle	0.67	−0.25
MV	Motor Vehicle	0.19	0.42
W	Wheelbarrow	0.35	−0.03
N	Seign Net	0.13	−0.21
P	Water Pump	0.20	−0.18
G	Genset/Water Tank	0.39	0.37

Composite Variable Name:
Dim1 = "Wealth"

(a)



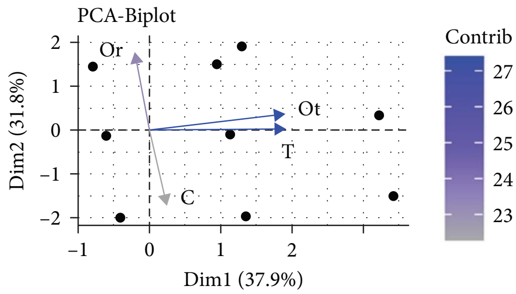
Social PCA

KEY		Dim1	Dim2
Ex	Years of Experience	0.58	0.82
V	Visits with Extension	0.75	−0.34
Co	Cooperative Member	0.76	−0.28

Composite Variable Name:
Dim1 = "More Social Connections"
Dim2 = "Experience"

(b)

FIGURE 4: PCA biplot and biplot key for variables describing (a) physical assets, and (b) experience and social connections. Each figure panel displays variance fractions captured by principal components, variance coordinates, and the label names assigned to each dimension. Red colored numbers denote a variable accounting for >0.50 of the variance coordinate, while colors within the "Contrib" scale of the biplot illustrate the percent contribution of each variable to the principal components.



Species PCA

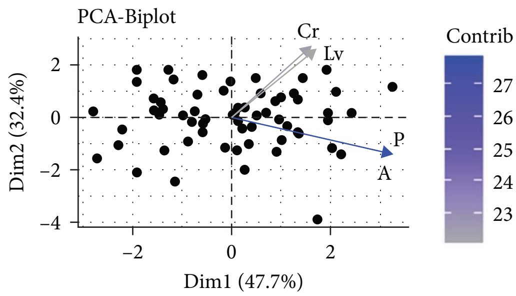
Key		Dim1	Dim2
Or	*Oreochromis* spp.	−0.10	0.80
C	*Coptodon rendalii*	0.10	−0.78
T	*Tilapia sparmani*	0.87	0.01
Ot	Other Fish Species	0.86	0.17

Composite Variable Name:

Dim1 = "Other Fish Species"

Dim2 = "Oreochromis vs. Coptodon"

(a)



Farm PCA

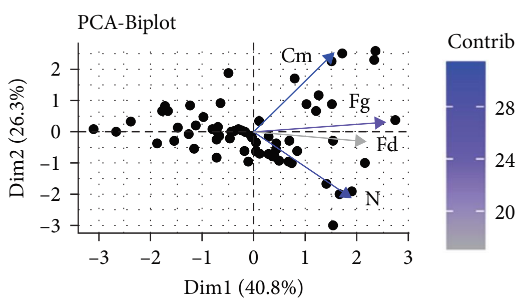
Key		Dim1	Dim2
A	Active Pond Area (m^{-2})	0.87	−0.37
P	Number Active Ponds	0.87	−0.36
Cr	Cropland (ha)	0.46	0.70
Lv	Livestock (TLU)	0.43	0.73

Composite Variable Name:

Dim1 = "Small vs. Large Fish Farm"

Dim2 = "More Cropland and Livestock"

(b)



Input PCA

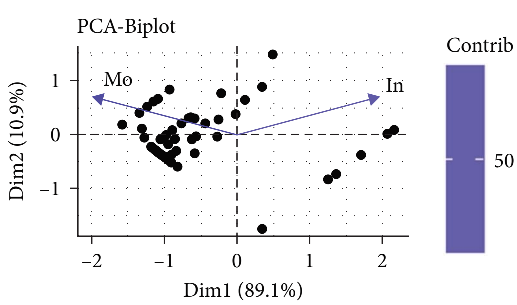
Key		Dim1	Dim2
N	Nitrogen g m^{-2}	0.58	−0.65
Fg	Fingerlings m^{-2}	0.78	0.08
Fd	Feed m^{-2}	0.67	−0.09
Cm	% Commercial Feed	0.48	0.78

Composite Variable Name:

Dim1 = "High vs. Low Input Rates"

Dim2 = "Fertilization vs. Commercial Feed"

(c)



Cycle PCA

Key		Dim1	Dim2
Mo	Growing Cycle (Months)	−0.94	0.33
In	% Yield Intermittently Harvested	0.94	0.33

Composite Variable Name:

Dim1 = "Extended vs. Shortened Growth Cycle"

(d)

Figure 5: PCA biplot and biplot key for variables describing (a) fish species, (b) fish farm structure, (c) input intensity, and (d) growing and harvest cycles. Each figure panel displays variance fractions captured by principal components, variance coordinates, and label names assigned to each dimension. Blue colored numbers denote a variable accounting for >0.50 of the variance coordinate, while colors within the "Contrib" scale of the biplot illustrate the percent contribution of each variable to the principal components.

along Dim1 (i.e. "Low vs High Input Rates"). Relative differences in between feeding and fertilization strategies (i.e. "More Fertilization vs. More Commercial Feed") were captured in Dim2. The PCA on growing and harvest cycles indicated that two distinct strategies existed. A cluster of farmers reporting extended growth cycles and bulk harvesting were oriented in

Table 3: Summary statistics of social–ecological model predicting productivity (kg Fish m^2 [log 10]).

Coeficents	Estimate	SE	*T* val	Pr (> | t |)	Sig.
(Intercept)	−1.571	0.122	−12.900	0.000	***
as.factor (hired labor in aquaculture)	0.079	0.094	0.084	0.405	—
Education score	0.092	0.048	1.941	0.057	.
Low vs. high input rates	0.060	0.034	1.752	0.085	.
as.factor (spatial integration with cropland)	0.166	0.078	2.114	0.039	*
Wealth	0.412	0.177	2.333	0.023	*
Extended vs. shortened growth cycle	−0.064	0.030	−2.168	0.034	*
Small vs. large fish farm	−0.081	0.030	−2.713	0.089	**

Note: Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '—' 1. Residual SE, 0.2927 on 55 df. Multiple R^2: 0.5024; Adjusted R^2: 0.4391; F, stat: 7.934 on 7 and 55 df, p-val = 1.251e−06.

the negative of Dim1, while farmers reporting no definitive growing cycle and only intermittent harvest strategies were oriented in the positive (i.e. "Extended vs. Shortened Growth Cycle").

3.3. Predictive Modeling. Summary statistics of the final social-ecological model predicting productivity (kg Fish m^2 [log10]) are presented in Table 3. The model included three social variables, four ecological variables, and generated an R^2 of 0.50. Social factors included the ownership of physical wealth, education level, and investments in hired labor. Ecological factors included the size of the fish farm, input intensity (i.e. fingerlings, feed, and fertilizers), length of growing cycles, and spatial integration of fishponds and cropland. Justifications for model fitness, including residual, standard residual, QQ plots are found in Figure S9. Start and stepwise stages of variable elimination (Models 1 and 2) are available in Table S2. The effect of each significant predictive variable in Models 1 and 2 is graphically represented in Figure 6.

Significant interactions ($p < 0.001$) existed between explanatory variables in the final model. A pairwise correlation matrix explaining interactions is provided in Figure S9. The wealth variable was weakly correlated with higher education levels ($R^2 = 0.256$; $p < 0.05$), higher input rates ($R^2 = 0.49$; $p < 0.001$), hired labor ($R^2 = 0.51$; $p < 0.001$), and extended growth cycles ($R^2 = -0.33$; $p < 0.01$). An interaction existed between "Small vs Large Fish Farms" and the spatial integration variable ($R^2 = 0.25$; $p < 0.05$), suggesting larger fish farms tended to be spatially integrated.

4. Qualitative Findings

4.1. Farmer Perceptions of Challenges. Participating farmers perceived a variety of challenges when managing aquacultural systems. Listed in order from most to least discussed major theme, farmers reported the following challenges: (a) fish feed; (b) preharvest loss; (c) labor and finances; (d) tools; (e) fingerlings; (f) water; and (g) other (Figure 7). A variety of sub-themes emerged from qualitative data analyses. The following findings address each major theme, relevant sub-themes, and applicable observational data.

4.1.1. Fish Feeds. Participants most frequently emphasized that their major challenges were related to feed resources (35% of responses). Three main sub-themes emerged: expense of high-quality feeds, the limited supply of high-quality feeds, and the low quality of available on-farm feeds. Farmers considered commercial feed and homemade feeds comprised of maize meal or soybean meal, as high quality. These inputs were crucial for achieving positive outcomes, such as "maximizing my production" and "making the fish grow quickly for us to sell" (ID63, 55 years old [*y/o*], male, 3 years' experience [*y*/exp.]). These feed types were also considered expensive, and their local supply inconsistent. For example, one participant stated:

Here where we live, business is very difficult, and we usually have little money. Sometimes there is feed shortage, at times we are charged a lot of money for transport to get [commercial] feed from Kasama, or… from Lusaka. Lack of… access to good feed locally is the biggest challenge (ID18, 74 *y/o*, male, 36 *y*/exp.).

This farmer expressed frustration regarding dependance on crop wastes, adding "though we have local feed, when we use it, the fish don't grow well at all." Others described similar frustrations, adding they used "cassava leaves only," describing these feed sources as "poor," "traditional," or otherwise associated with adverse outcomes. One farmer claimed low feed quality caused "reduced… duration for harvest to only once per year" (ID11, 57 *y/o*, male, 8 *y*/exp.).

Fertilization was not perceived by farmers as a significant challenge. However, differences in fertilization strategies were noted by researchers. Well fertilized ponds (Figure S3) often contained waters tinted with green colors, signifying algal biomass developed by natural or artificial fertilizers [47]. Some farmers gestured towards steeped bags of manure, or fresh additions of "green manure" vegetation. Conversely, other fishponds contained clear waters, a sign of poor fertilization and shallow pond depths, or murky waters, which were less easy to discern.

4.1.2. Preharvest Loss. Pre-harvest loss of fish was the second most frequently cited challenge (23% of responses; $n = 33$ farmers). Wild predation and human theft were the most frequently identified sub-themes. For example, a farmer stated that "security from predators, [including] birds and small animals…is difficult during the day and night" (ID17, 49 *y/o*, male, 2 y/exp.). Ponds were "at the mercy" of predators commonly "found in the plain," such as "birds," and "water monitors."

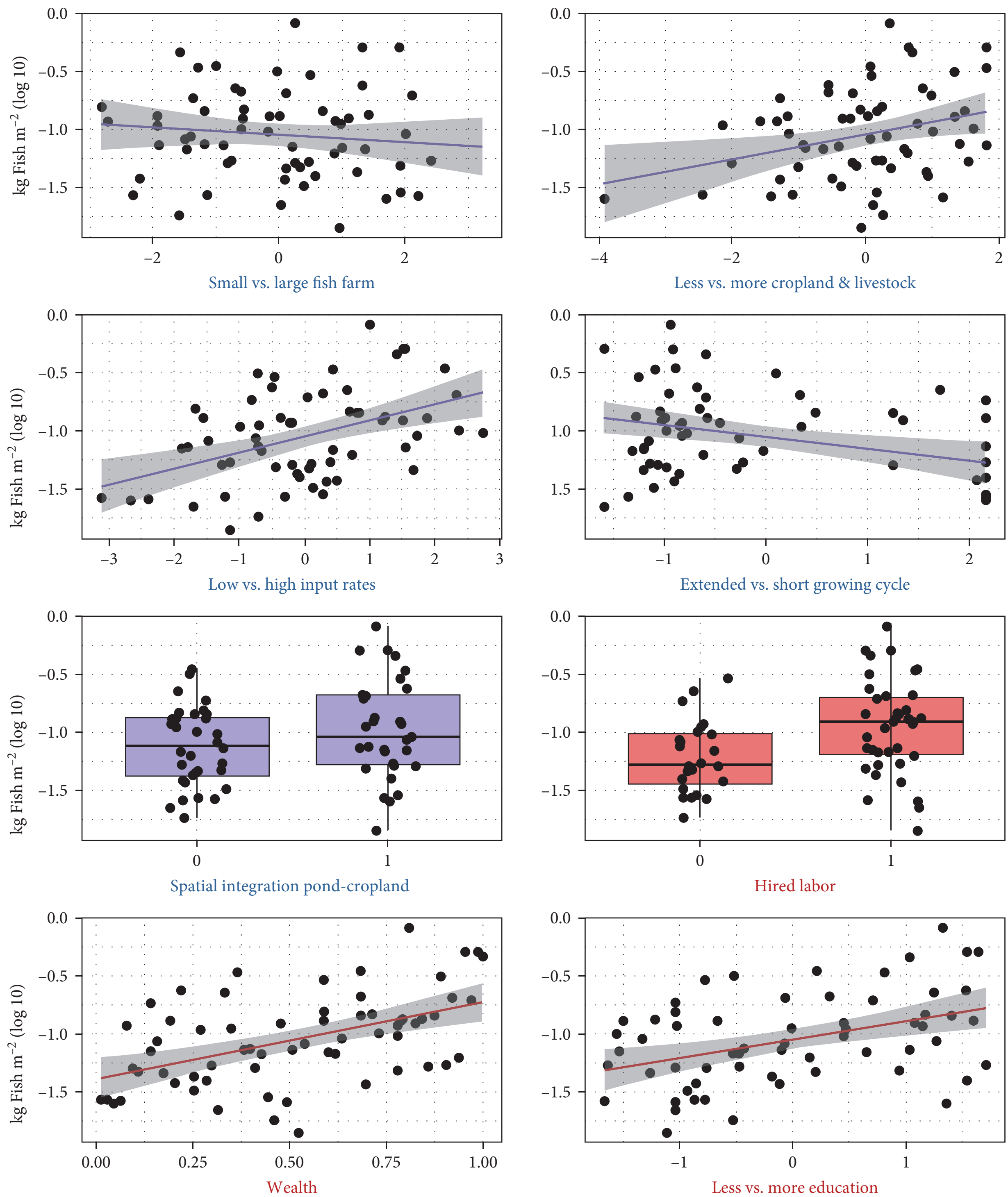


Figure 6: Social and ecological factors that influenced productivity in aquaculture systems.

Four participants emphasized their biggest concern was otters (*Aonyx capensis*).

One response typified sentiment regarding both predation and theft: "The challenge is predators… Even thieves are predators! A human is predator number one" (ID1, 61 *y/o*, male, 11 y/exp.). Farmers described local people who "come using nets" to "steal the fish" and "leave the ponds broken." Farmers felt "discouraged." Even those with ponds next to the house reported theft. Loss occurred "when [the family] was out," for example attending "church programs" (ID30; 43 *y/o*, male, 3 y/exp.). Only three wealthier farmers protected their fishponds with a chain-link fence, and all three cited pre-harvest loss as a challenge. Compared to fences, other low-cost strategies to prevent losses were observed more frequently (Figure S4). Farmers

Challenges	
Feed	35%
Fingerling	9%
Tool	11%
Pre-harvest loss	23%
Water	5%
Labor & finance	13%
Other	3%
	Total: 100%

Sub-theme	
Resource is expensive	34%
Resource is unavailable	28%
Resource is poor quality	12%
Predation	20%
Disease	2%
Other	3%
	Total: 100%

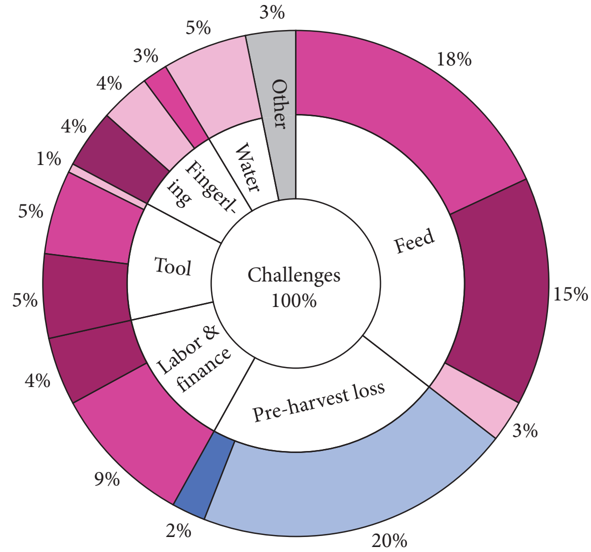


Figure 7: Farmers described up to 3 challenges experienced when managing aquacultural systems ($n = 63$ farmers; 186 total challenges). This diagram summarizes major themes and sub-themes of each reported challenge.

erected physical barriers within the pond to impede dragging of nets or free movement of swimming predators. One participant staked and stretched brightly colored strings in a zig-zag pattern to deter predation from eagles.

4.1.3. Labor and Finances. About 25% ($n = 17$) of farmers reported that access to labor was a major challenge (13% of responses). All farmers expressed a desire for successful management; however "the work is intense" and "money to hire labor is difficult to find." Discussions frequently oriented around digging and maintenance activities. Establishment of a new fishpond was "quite difficult and requires one to be very determined and hard working to be able to manage" (ID63; 55 *y/o*, male, 3 y/exp.). Some farmers who hired workers to complete the task considered the expense a significant challenge. For example, a farmer stressing his finances in pond establishment said:

> *Pond digging requires about…1000 kwacha [ZMW for hired labor; $58 USD] ….and for about 600 fingerlings, it will cost about 900 kwacha. This totals 1,900 kwacha. But the people who are digging the pond also require food while they work. This comes to [total] about 2000 kwacha [ZMW; $116 USD]…[this] is very difficult. I haven't yet harvested this pond because of [recent construction]. (ID35, 43* y/o*, male, 3* y/exp.).

Other than discussions regarding pond digging, a minority of farmers described challenges in conducting basic management, like proper feeding, harvesting, or pond cleaning. Agriculture demanded the household's attention, and labor in aquaculture was "difficult in terms of dividing time with other activities which we are involved in" (ID38, 75 *y/o*, male, 4 *y*/exp.). In these cases, management could improve in aquaculture if additional labor could be afforded.

4.1.4. Tools. About 30% of farmers ($n = 19$) cited the lack of appropriate tools as a major challenge (11% of responses). Access to a seine (Figure S5) was most frequently discussed. Notably, not present in these conversations were farmers owning seines, who reported a timely harvest, followed by the borrowing or renting of their nets to other farmers. Since demand was high and transportation was difficult, waiting times for rented or borrowed nets were lengthy. Some farmers expressed frustration since they could not plan and conduct proper harvest:

> *We have only one common net which goes around to all the farmers in far flung areas of about 60 kilometers apart. So, it takes time for it to come around. (ID14, 51 y/o, male, 5 y/exp.)*

Farmers without access to seine nets reported alternative strategies. Alternatives were few and depended on pond size. Those managing smaller ponds used traditional reed nets, or homemade nets created from multiple, recycled, mosquito-nets stitched together. The most common alternative was draining the pond. A few farmers considered this strategy risky because "pond draining method… leads to the loss of fingerlings" (ID10, 38 *y/o*, 14 y/exp.). For example, when asked to clarify concerns over pond draining, one farmer gestured towards nesting sites of *C. redallii* in the sediments adjacent to the pond dikes (Figure S6). For this farmer, maintaining water levels and use of a seine was the safest and most efficient means for dividing fingerling or brood stock from harvested fish.

Equipment other than nets was discussed less frequently. Some farmers reported "tools for digging and taking care of ponds" were needed, but there was a "lack of funds to buy them." Tools inventoried in these discussions included shovels, wheelbarrows, water pumps, weighing scales, chain link fencing, as well as "water quality testing tools," and "feed-making equipment."

4.1.5. Fingerlings. Approximately one-third of participants ($n = 19$) considered the sourcing of fingerlings a challenge (9% of responses; Figure S6). Many farmers stressed poor genetic quality of available fingerlings and worried that inbreeding reduced productivity of their ponds. For example,

> *A source for fingerings here is rare. People raise the same breed of fish for 5 years without changing. (ID65, 24 y/o, male, 2 y/exp.).*

In many conversations, farmers perceived fingerlings as difficult to locate and expensive when accessed. The average reported cost was 1.4 ZMW ($0.08 USD) per fish, depending on provider and cost of transport. Local supply was a key challenge. Only a few local farmers sold fingerlings, and "the supply is inconsistent." One farmer explained:

> *We have [a fellow farmer] who produces fingerings. He is the only one in this area, and there are many people now who would like to buy fingerings. As a result, there is a queue. You go and register and wait for many months before you are provided with [fingerlings] (ID48, 63 y/o, male, 7 y/exp.).*

Some participants perceived local suppliers of fingerlings "lack good variety" or sold only "one breed of pale [*Oreochromis* sp.] which doesn't grow very big no matter how you feed it." These inconsistencies in local supply and quality motivated several farmers to source fingerlings from the government hatchery in Kasama. In these cases, added time and travel expenses were challenges.

4.1.6. Water. Observational data were collected at the height of the dry season. Water was not perceived as a major constraint for most farmers. Nearly all farmers were observed with active ponds on-site; however observations of shallow wells with stagnant flows or dried furrows were also noted (Figure S8). Two farmers reported their total pond area was completely dry, however an additional eight farmers owned at least one pond that was failing to retain water. Farmers with multiple ponds did not perceive pond drying as a major challenge, noting that aquacultural activities were shifted to newer ponds with more reliable water volumes.

Eleven farmers reported their major challenge was poor water quality due to dry conditions (5% of responses). For instance, one farmer noted,

> *We seem to have limited water sources for filling up ponds…the water is drying up bit by bit to the point where the fish…can easily be seen (ID25, 57 y/o, male, 2 y/exp.).*

Water quality "was not adequate" during "some months of the year" when "rains were insufficient." There was "inadequate water to sustain the ponds" which led to "diseases." One farmer added, "when the water is hot, the fish die" (ID33; 36 *y/o*, male, 3 y/exp). The intensity of labor needed to mitigate pond drying was also emphasized. This included activities like re-digging the wells and furrows to access dropping water tables. For example, one farmer gestured to multiple shallow-dug wells on the property, expansive digging projects, and shallow water levels, and stressed that "works involving maintenance of the ponds are hectic" (ID5, 49 *y/o*, female, 2 y/exp.).

Lasty, two farmers indicated that low water availability was the result of household priorities during the dry season. For example, one farmer owned ponds which were completely dry and reported that "water supply in the furrow to satisfy…the many uses at the farm is inadequate" (ID61; 55 *y/o*; male; 2 y/exp.).

4.1.7. Other. Several "other" challenges were notable. Access to technical knowledge and extension services was reported by six farmers (3% of responses) as a significant challenge. Some farmers perceived they lacked knowledge in the "area of fish feed" and "pond digging techniques." Finally, two farmers admitted they had "limited time," and aquaculture was "not a priority."

4.2. Farmer Perceptions of Aquaculture's Benefits. Farmers frequently communicated success in aquaculture during open-ended discussions, and this is noteworthy. Most participants ($n = 56$; 89%) reported that they were satisfied with being a fish farmer. When asked to qualify, the immediate benefits of income generation and consumption were cited. Farmers who reported income from aquaculture used the money for immediate household needs. This included using the income for hired labor in both aquaculture and agriculture, school fees, clothes for children, maize meal, and bags of building sand. Farmers emphasized that aquaculture "has many benefits in a short period of time." For example, one farmer noted that "in six months we are able to harvest and get good money as compared to maize" (ID29, 70 *y/o*, male, 5 y/exp.). Several farmers made comparisons between outcomes in aquaculture and agriculture. For example,

> *[Aquaculture] is beneficial as compared to crop farming. For example, I once tried to make a [10 m x 10 m] pond, and the harvest I got from aquaculture was far better compared to a [10 mx 10 m] portion of maize, in terms of profit. (ID37, 51 y/o, male, 4 y/exp.).*

Lastly, three farmers relying on aquaculture for subsistence purposes discussed the food security benefits of aquaculture, emphasizing that ponds were an important resource "in November and December" when there was "difficulty in finding relish [food]" (ID21, 31 *y/o*, male, 9 y/exp.).

5. Limitations

This study focused on a small sample size ($n = 63$) of fish farmers. Generalizability of results and conclusions is low. Sampling techniques incorporated both random and snowball approaches, thus the sample may not be representative of fish farmers in the region. For instance, the average farmer in this study was more experienced than the average fish farmer in the district. Thus, dominant perceptions might not accurately reflect the experiences of new adopters or those with more limited access to resources. Future studies could address these limitations by increasing sample sizes and adopting random sampling techniques to obtain more robust and representative samples. Additionally, the inclusion of multiple study regions would allow an understanding of system variation across landscapes.

Data collected in this study described only one agricultural season, which is insufficient to understand aquaculture's long-term functioning. Smallholder farms are complex, having multiple actors, interactions, and feedbacks between human and ecological components. It is recommended that future research adopt longitudinal study designs to understand interactions between system components, particularly during periods of ecological or economic shocks.

This study makes inferences based on social data and participant memory recall. Results were subject to bias common to many development studies relying on these methods [48]. Social data is inherently subjective, and despite the rigorous qualitative procedures adopted by researchers, both researcher and participant expectations may have biased the framing of questions or responses. For instance, during memory recall, some participants may have been unaware of aquaculture system complexities and impacts on productivity, especially regarding biophysical factors such as water quality or fish health.

Biophysical measures were not collected in this study. Previous studies investigating biophysical constraints of *Oreochromis niloticus* production within smallholder systems have indicated that dissolved oxygen (DO) in pond water, water temperature, and pH, were key influences on feed conversion ratios and pond production potentials [49]. Thus, future studies should consider integrating social, economic, and biophysical indicators of productivity to more fully understand the contributions of each component to system functioning.

6. Discussion

General descriptions of aquacultural systems management and outcomes in this study align with recent studies conducted in the region [11, 14–16, 21]. Most farmers considered aquaculture to be a secondary or tertiary livelihood activity. Systems varied according to extensive and semi-intensive input functions, as well as subsistence and semi-commercial output functions [14, 50]. In this study, as in other studies, wealthier farmers reported greater access to feed, seed, and labor inputs, which were key determinants of productivity. Poorer farmers tended to report more extensive forms of management, characterized by the recycling of on-farm fingerlings over several years, short or unclear growing cycles, and reliance on only crop waste or vegetation as feed inputs. Such practices are known to be associated with low productivity [18]. Most farmers, however, reported some form of semi-intensive management, characterized by more prolonged growing cycles, or investments in fingerling, feed, fertilizer, and labor inputs. The range of productivity reported by farmers in this study was comparable to other estimates derived from recall data in Northern Province (0.5 to 3.1 t ha^{-1}; [16, 32]). The mean yield in this study (1.2± 1.2 t ha^{-1}) was comparable to Lundeba et al. [21], who conducted controlled, on-farm production trials, resulting in yields ranging from 1.61 to 1.9 t ha^{-1}.

Smallholders identified numerous challenges in their management of aquacultural systems. Several themes were consistent across all discussions. Management was constrained by limited finances, high costs, and inconsistent local supplies of quality inputs. Local sources for fingerlings, commercial feed, and essential ingredients used in homemade feed were in short supply and infrequently available. Quantitative results aligned with farmers' perceptions, suggesting that increased numbers of stocked fingerlings, and total quantities feed and fertilizers achieved more productive outcomes. Most farmers, however, emphasized feed was a more immediate challenge. Feed supply is frequently emphasized as a primary barrier to aquaculture in Africa, as the input accounts for more than 60% of costs in profitable semi-intensive aquaculture enterprises [51]. Development of the local feed value chain is a potential pathway to generate productivity for smallholders [17]. Research has focused on identifying local and farm-generated protein and energy supplements that are noncompetitive with household needs, have high nutritional content, low prices, and regular availability in the local context [52, 53]. Examples of these alternatives include cassava root meal, sweet potato meal, moringa leaves, and insects [17, 53, 54].

In quantitative analyses, variables describing social connections showed no statistically significant effects on productivity. However, qualitative findings highlighted the importance of social networks to support labor, finance, and resource access. Professional, cooperative, or personal relationships with other community members determined access to many inputs, such as seine nets, feeds, fingerlings, and labor. For instance, other than hiring workers, some farmers described pooling labor resources within cooperatives to harvest or dig new ponds or organizing with fellow fish farmers to share costs in transportation and bulk purchases of commercial feed or fingerlings. Development stakeholders consider policies strengthening self-organized, local professional organizations and cooperatives an imperative for the sustainable growth of smallholder aquaculture [11, 14, 19]. These arrangements help integrate smallholder operators into markets and facilitate uptake of new technologies and better management practices [19]. For example, coordinating with farmer networks is considered a viable strategy for increasing the supply of fingerlings in Northern Province. Studies recommended policies that support public, private, and small-scale hatcheries to generate both income and local fingerling supply [11, 12, 14]. This includes decentralized operations, such as local and small-scale household hatcheries, hapa nursing, and trading networks [55].

To overcome initial costs and increase access to feed and fingerling inputs, development stakeholders have proposed increasing the supply of microfinance to smallholders with commercial orientations [14]. Because loans and microfinance schedules are customarily tailored to crop production seasons, it is recommended that repayment schedules be tailored to accommodate the unique needs and timelines of aquaculture [56]. Such targeted microfinancing policies could strengthen local networks of private nurseries and hatcheries, thus improving flow of fingerlings throughout the communities [14]. Microfinance programs, however, should not be considered a "silver bullet." Van Rooyen et al. [57] conducted a systematic review of 35 studies measuring impacts of microfinancing in sub-Saharan Africa. The authors concluded that impacts were modest, nonuniform, and in some cases, crediting negatively impacted wealth creation. In these cases, households consumed instead of investing in the future, businesses failed to produce sufficient profit to repay the interest, or long-term investments resulted in insufficient returns for repayment [57].

In this study, poorer households adopted shorter growing cycles, combined with intermittent harvesting—strategies known to be associated with inbreeding, stunting, skewed sex ratios, and lower productivity in tilapia production systems [58]. Agroecological innovations should consider optimal species and spatial arrangements that provide for the "intermittent" needs of these poorer households. Tilapia production may require companion activities with shorter cash flows and harvest cycles that relieve the harvest pressure on larger species, allowing fish to grow to a more uniform and marketable size. Polyculture technologies are one innovation which may provide such opportunities. Polyculture seeks to pair compatible fish species that exploit different niches in pond ecosystems, thereby increasing resource-use efficiency and production per unit area of pond [59, 60]. Recent studies in Northern Zambia have tested compatibilities of larger native tilapias (*O. machocir*, *T. sparrmanii*) and pelagic small fish (*P. philander*, *B. trimaculatus*) [31, 61]. Small fish are common recruits in aquaculture systems and—since they are traditionally eaten whole—provide richer sources of micronutrients compared to commercial species of tilapia [62, 63]. Research on small fish polycultures in Bangladesh found benefits to livelihood via shorter production cycles, faster cash flows, and intermittent provisioning of nutritious fish throughout the season [64, 65]. To become a viable pathway in African contexts, small fish polycultures require further research and development. Currently, no best practices exist for stocking/recruiting and managing small indigenous fish species in Zambia, and little is known regarding productivity potentials, or farmer's willingness to adopt such practices.

In this study, higher productivity was reported by farmers with integrated arrangements of aquaculture and cropland. The exact mechanism by which productivity was increased was undetermined. However, participatory on-farm trials in Tanzania have demonstrated some potential benefits of integrated practices [10, 66]. Limbu et al. [10] conducted a 270-day, controlled, IAA production study in Tanzania which compared the yield and economic benefit of integrated vegetable-fish systems to fish-only and vegetable-only systems. Integrating aquaculture with vegetables resulted in significantly higher annual net cash flow, as well as 3.0- and 2.5-times higher net yields when compared to fish-only and vegetable-only treatments, respectively. This "over-yielding" was attributed to shorter production cycles of vegetables compared with fish culture, as well as high nutrient concentrations within the irrigation water supplied by pond systems [10]. It is notable that, like the on-farm trails of small fish polycultures in Bangladesh, the authors emphasized the short-term financial and nutritional benefits of small gardening as a companion activity to aquaculture.

Results regarding the demographics of participants in this study suggested aquaculture was mostly adopted by older men. Females and youths made up a small fraction of fish farmers sampled, and these findings align with provincial reports [35]. Zambia demonstrates high national rates of youth unemployment. The average age of farmers is 46 and individuals younger than 35 years comprise only 24% of all farmers in the country [18]. In rural areas, gender norms within households, value chain governance structures, and institutions, restrict women's access to land and other national resources, thereby contributing to aquaculture's under-performance [67, 68]. Access to and control over resources are intimately connected with the ability of women and youths to exercise their agency and to participate effectively in aquaculture [68–70]. Policies and programs that promote aquaculture, including field schools, extension services, and collaborations between farmers and researchers, should incorporate more transformative, gender-sensitive, and youth-centered approaches [70].

Findings from this study align with previous observations made by extension professionals regarding a need for training in water system management, planning of growing cycles, and record keeping [14, 16]. For example, observational data suggested that, rather than dry conditions, water management was most impacted by poor site evaluation and methods of construction. Previous studies have found that although most farmers maintain adequate water levels for fish culture, rates of water seepage are high and often offset by the placement of ponds in low-lying swamps [16]. This was observed in the current study as well (e.g., see Figure S10). Best management advises that farmers consult extension professionals before selecting a suitable area, since water conditions may change in relation to topography, water source, and soil characteristics [18]. Few farmers receive such consultation, and most ponds are poorly placed and constructed [14, 16]. Such expansion of aquaculture into sensitive wetland ecosystems without simultaneous investments in technical efficiency and productivity is considered socially and environmentally unsustainable [14]. Studies from both Africa and Asia demonstrate chronic disruptions may emerge from the "grabbing" of land and water resources when economic prospects of agriculture or aquaculture grow [71–73]. These conditions reduce the functionality of community-based water management schemes and jeopardize local livelihood. Mitigating such degradations to the natural resource base becomes critical when accounting for changes to tilapias' survival, growth, and production in present and future conditions of climate change. Long-term climate projections of Southern Africa predict warming, drought, flood, and rainfall variation [74]; conditions likely to reduce groundwater inflows that currently offset high rates of water seepage in Northern Province.

7. Conclusion

Numerous studies have outlined the challenges to aquaculture's development at national and regional scales. This study focused on the local-specific context and explored the social and ecological factors influencing productivity for smallholders in Luwingu District. This study added to the existing body of research regarding farmer perceptions, aquaculture production constraints, as well as potential innovations to overcome these constraints. In discussions, smallholder farmers emphasized limited finances, high costs, inconsistent supplies of quality inputs, and pre-harvest fish losses. Analysis of survey data indicated wealth, education, and access to hired labor were key social determinants of productivity. Ecological determinants included the farm size, intensity of feed and fingerling input, length of growing cycles, and spatial integration of fishponds and cropland.

Innovative and locally adapted strategies to increase productivity are needed in Luwingu. Potential pathways in this region include policies which support technical efficiency in feeding and breeding practices, planning of growing cycles, water resource management, and business. Aquaculture extension programs should incorporate gender sensitive and youth centered approaches to expand access to access to essential technical knowledge and resources. Policies which strengthen public and private fingerling production, farmer-to-farmer networks, linkages to commercial value chains, and microfinancing may further improve local access to inputs.

This study provided new insights regarding integrated systems. In quantitative models, aquaculture's integration with crop and garden systems was a major determinant of productivity. Integrated systems are under-researched in Zambia. It is recommended that future studies explore local-specific cropping arrangements and integrated management regimes that are most associated with productivity in different contexts of vulnerability and resource access. Additionally, production trials using participatory approaches are recommended to test aquaculture system performance within different integrated-agricultural treatments. This includes cropping arrangements commonly adopted by resource-rich as well as resource-poor households. Appropriate companion activities should provide for intermittent financial and nutritional needs of poorer households and relieve harvest pressures from tilapia during the aquacultural growth cycle.

8. Human Subjects Protection

Approval for this study was obtained in both 2019 and 2021. Ethics reviews were conducted in the United States (Pennsylvania State University; IRB00013899) and Zambia (ERES Converge; IRB00005948). Researchers were trained in human subjects' protection and adhered to all protocols. Participant privacy and confidentiality were maintained.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Jacob W. Johnson: conceptualization, funding acquisition, project administration, investigation, methodology, formal analysis, visualization, writing – original draft. **Michael G. Jacobson:** project administration, resources, supervision, validation, writing – review and editing. **Steven M. Cole:** project administration, resources, supervision, validation, writing – review and editing. **Muleya Syapwaya:** data curation, investigation, writing – review and editing. **Alexander Kaminski:** validation, resources, writing – review and editing. **Heather Karsten:** validation, visualization, writing – review and editing. **Jay R. Stauffer Jr.:** validation, writing – review and editing. **Leif Jensen:** validation, writing – review and editing. **Mary Lundeba:** resources, validation, writing – review and editing.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting Information 1. Table S1. Descriptive statistics of variables describing participants, households, and aquacultural systems within the study sample and Luwingu District. District data was summarized from the 2020 smallholder fish farmers population census report [35]. Sample data was deemed largely representative of the district. Distribution of demographic characteristics were comparable, including the reported sex, education, and marital status of household heads, as well as household sizes. Descriptions of aquacultural resources and systems of management were likewise comparable. A few potential differences were noteworthy. Sampled fish farmers appear, on average, older and more experienced than the average farmer in the district. Sampled farmers also reported owning more fishponds and were more likely to report using commercial and supplemental feeds. Table S2. Start and stepwise summary statistics of Output Models 1 and 2 predicting productivity (kg Fish m^2 [log10]). Figure S1. Household food waste and vegetation: (a) The use of household food waste (*ubwali*), and crop waste like (b) dried cassava root chips, (c) cabbage leaves, and (d) cassava leaves were frequently observed during interviews. Figure S2. Commercial feeds: (a) The use of commercial feeds was observed during several interviews. (b) The local feed shop had stocks of feed (c, d) available for about 2 weeks during the data collection period (October–December 2021), however they were quickly sold out. Figure S3. Fertilization strategies: (a) Waters of well fertilized ponds often displayed a green tint. (b) A common fertilization strategy was the use of compost cribs, stocked with "green manures" like grasses and plant leaves. Well-managed cribs were routinely cleaned to remove carbon. The addition of manure in bulk was not observed, however some farmers maintained (c) steeped bags of livestock manure, which were (d) periodically disturbed to release nutrients into the water, and eventually, (e) the remaining carbon-rich material within the bag was discarded. Figure S4. Preharvest loss: (a) One farmer staked and stretched brightly colored strings across his ponds to deter eagles. (b) The most common deterrent against wild predators and theft were stakes arranged to impede swimming and the dragging of nets. Farmers who owned fences were also observed, such as the chain-link fence in the background of Supporting Figure 6a. Figure S5. Tools: (a) Most farmers conducted digging and maintenance activities with basic agricultural tools. A small proportion of farmers owned (b) generated pumping equipment and water saving technologies, (c) treadle pumps, or (d) feed making equipment. (e) Seine nets, which were rented or borrowed from other farmers, were a frequent topic of conversation. (f) Some farmers were unable to access seine nets and used other methods, like traditional reed nets. Figure S6. Fingerlings: (a, b) Several small-scale fingerling producers were participants in this study. The use of hapa nets was also observed on some farms not producing fingerlings for sale. (c) Farmers considered the fingerlings that were generated on-farm as a valuable resource. (d) For example, a few farmers worried that harvesting by pond draining methods jeopardizes on-farm fingerlings, and the nesting of *C. redalli*. in pond banks. Figure S7. Water Resources: Most farmers dug shallow wells on the edge of a wetland, either accessing (a) groundwater or (b) a natural spring, then furrowing the water to their ponds. Other farmers redirected water from a river or stream using (c) personally managed or (d) community managed furrow networks. Figure S8. Water Resources and Methods of Construction: A few farmers in this study experienced challenges with their water resources, due to the (a) intensity of labor required to maintain water levels, (b) ponds failing to retain water, or ponds with diminished water levels, which caused water quality concerns (un-depicted). The ponds in panels (c) and (d) were topics of conversation with one farmer, who expressed concerns that his water resource was jeopardized by neighboring farmers, who were recent adopters and untrained in pond construction. Picture (c) shows a series of abandoned ponds constructed within the wetland, next to a stream channel. Picture (d) shows a large pond constructed off-contour. Figure S9. Pairwise correlation matrix of variables predicting productivity in aquaculture. Figure S10. Assumption tests for linear Model 2 describing productivity.

Supporting Information 2. Document S1. PhD Dissertation; Johnson, J. W. (2023). Integrated agriculture-aquaculture (IAA) systems in Zambia: A case study of aquacultural system management and farm diversity in two districts of Northern Province. The Pennsylvania State University.

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